Submitted to the IAA Conference on Low-Cost Planetary Missions held at JHU/APL, April, 1994.

A SMALL INTERSTELLAR PROBE TO THE HELIOSPHERIC BOUNDARY AND INTERSTELLAR SPACE

R. A. Mewaldt
California Institute of Technology
Pasadena, CA 91125 USA

J. Kangas, S. J. Kerridge, and M. Neugebauer
Jet Propulsion Laboratory
Pasadena, CA 91125 USA

ABSTRACT

The Small Interstellar Probe mission would be designed to cross the solar wind termination shock and the heliopause, and make a significant penetration into nearby interstellar space. The principal scientific objectives of this mission would be to explore the structure of the heliosphere, to investigate its interaction with the interstellar medium, and to explore the nature of the interstellar medium itself. These studies would be carried out by a ~200 kg spacecraft carrying a scientific payload designed to make comprehensive, *in situ* measurements of both heliospheric and interstellar plasma, fields, energetic particles, gas, and dust. New trajectory calculations indicate significantly improved performance over earlier studies with larger spacecraft, including spacecraft velocities ranging from ~6 to ~14 AU/yr., depending on trajectory and launch vehicle.

INTRODUCTION

In our present view of the large scale structure of the heliosphere (Figure 1), the solar wind flows radially outward to a "termination shock", surrounded at somewhat greater distance by a surface called the heliopause, which is the boundary between solar wind and interstellar plasma. A bubble of solar wind therefore shields the inner heliosphere from the plasma, energetic particles, and fields of the interstellar medium (ISM); to observe these directly one must get outside the heliopause. Figures 1 illustrate the expected plasma and magnetic field profiles. Although the size of the heliosphere is not certain, several recent estimates place the termination shock at a distance of ~70 to 100 AU, with the heliopause somewhat further beyond (see, e.g., Holzer[1], and Suess[2]).

In March, 1990 NASA's Space Physics Division sponsored a workshop in Ballston, VA to study the scientific rationale, measurement objectives, and instrumentation requirements for an Interstellar Probe Mission, whose primary objectives would be *in situ* measurements of the particles, plasma, and fields at the boundary of the heliosphere and in local interstellar space. The results of this workshop appear in a report[3] *"The Interstellar Probe: Scientific Objectives and Requirements for a Frontier Mission to the Heliospheric Boundary and Interstellar Space,"* and this mission is included in the long range plan of the Space Physics Division 1991 Strategy/Implementation Study[4]

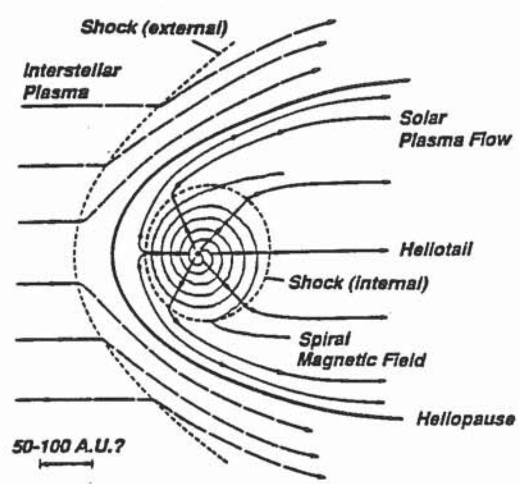


Figure 1: Schematic Illustration of a plausible structure for the heliosphere.

Figure 2: Expected density profiles of heliospheric and interstellar ions and gas for a termination shock assumed to be located at ~50 AU. The horizontal line indicates the sensitivity and expected distance range over which measurements of solar wind protons will be carried out by Voyager 2

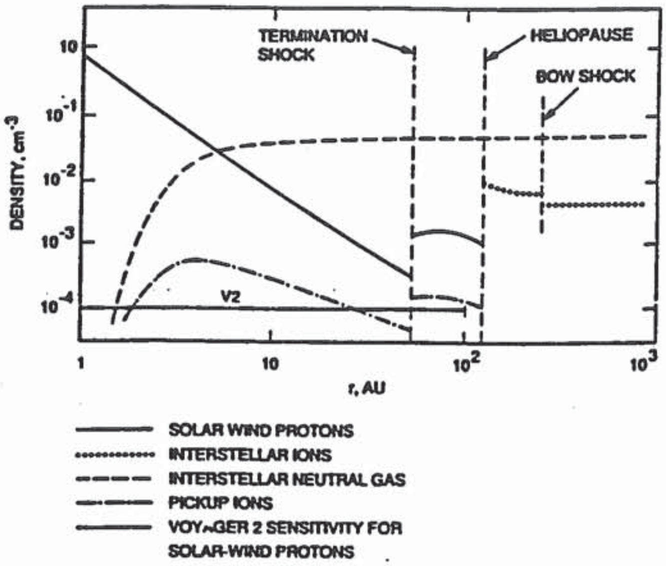
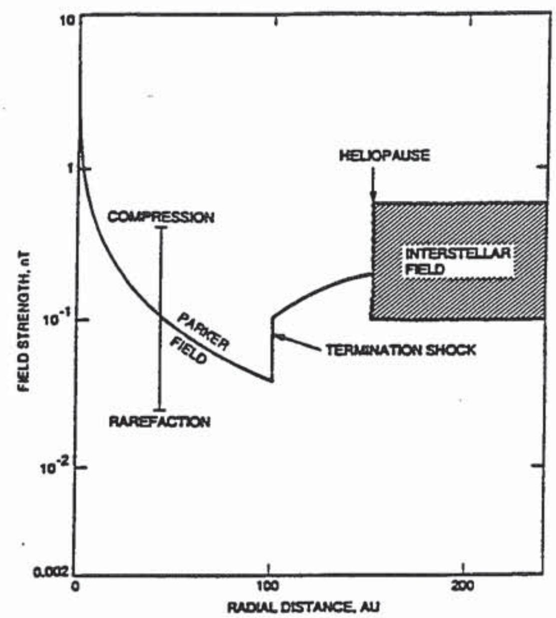


Figure 3 (at right): Expected variation of the magnetic field strength in the outer heliosphere and beyond. Typical variations in the interplanetary field are indicated. Here the termination shock is assumed to be at 100 AU. The interstellar field strength is poorly known



In the 1990 study, a strawman scientific payload, requiring a mass and power of 125 kg and 96 W, was identified to make comprehensive, *in situ* measurements of heliospheric and interstellar plasma, fields, and energetic particles out to a to a radial distance of ~200 AU. This payload would have required a spacecraft mass of from ~600 to 1000 kg. While technically feasible, the costs associated with a mission of this size are beyond current budgetary guidelines.

Advances in spacecraft and instrument technology over the past few years have demonstrated that state-of-the-art measurements can now be accomplished with new approaches that require greatly reduced mass and power[5]. In addition, there is now strong emphasis within NASA on new technological developments, and on "faster, better, and cheaper" spacecraft that appear to be well-suited to this and similar exploratory missions. Inspired by those developments, and by the recent heightened scientific interest in the boundaries of the heliosphere, we have, over the past year, considered possible implementations for a "Small Interstellar Probe" mission. We report here on new trajectory options that offer improved performance for small spacecraft, and suggest a strawman scientific payload that would accomplish the primary scientific objectives of this mission for greatly reduced resources.

RATIONALE AND SCIENTIFIC OBJECTIVES

The principal scientific objectives of the Small Interstellar Probe Mission remain essentially the same as those identified in the 1990 report[3]. They include:

- **Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in the Galaxy.**

Our knowledge of the local ISM is surprisingly limited (e.g., Figures 3 and 4). Direct measurements of interstellar plasma and neutrals, magnetic fields, and unmodulated cosmic ray spectra would delineate the pressure and energy balance of the local ISM and assess mechanisms for the ionization, heating, and dynamics of interstellar gas. Measurements of the elemental and isotopic composition of the interstellar gas and cosmic rays from H to Ni ($Z = 1$ to 28) would provide crucial information for studies of the chemical evolution of the Galaxy and the origin of the solar system. Electron measurements would probe the galactic nonthermal radio emission, while positron studies, if possible, might find evidence of recent nucleosynthesis. Interstellar Probe could also provide a unique baseline for locating cosmic γ-ray bursts.

- **Explore the structure of the heliosphere and its interaction with the interstellar medium.**

Interstellar Probe would investigate the location and motion of the termination shock and investigate its detailed structure, including the roles of thermal gas, suprathermal pickup ions, and anomalous cosmic rays in determining shock structure. Multiple shock crossings are very possible. Interstellar Probe would also investigate the structure of the heliopause, search for a heliospheric bow shock, and measure the penetration of gas and dust into the heliosphere. The boundaries of our heliosphere provide a model for similar interactions occurring around stellar systems throughout the Galaxy.

- **Explore fundamental astrophysical processes occurring in the heliosphere and the interstellar medium.**

Particle acceleration is ubiquitous in nature. *In situ* observations in the outer heliosphere and at the termination shock would investigate the shock acceleration of anomalous cosmic rays and other species from their seed population to the limits of the acceleration mechanism. Detailed measurements of the microscopic and macroscopic shock structure are of general interest because of the broad significance of shocks in astrophysical systems. Interstellar Probe would also study the turning of the subsonic solar wind and the interstellar plasma flows on the upstream side of the heliosphere. including effects due to thermal pressure gradients, magnetic fields, and interstellar neutral gas.

<u>Recent Related Results</u>

Scientific interest in the boundaries of the heliosphere has recently increased as a result of new discoveries by the Voyager, Pioneer, and Ulysses missions. For example, the Voyager plasma wave experiments have discovered radio emissions from the direction of the nose of the heliosphere that appear to be triggered by large interplanetary shocks propagating beyond the heliopause. Analysis of those emissions suggests a heliopause distance of 116 to 177 AU in 1992 near solar activity maximum[6]. In a separate study[7], an extrapolation of the intensity gradients of anomalous cosmic rays measured between Voyager 2 at ~20 AU and Pioneer 10 at ~40 AU during the 1987 solar minimum gives an estimated distance to the termination shock of 67±5 AU. Although they relate to different phases of the solar cycle, these shock and heliopause estimates appear to be consistent with theoretical models of the heliosphere if the heliopause distance is near the lower end of the estimated 116 - 177 AU range.

Several other recent results have confirmed the present view of the large-scale heliosphere. Instruments on Ulysses have now detected directly interstellar neutral He penetrating into the inner solar system, and have identified so-called "pickup" ions of H, He, O and other elements that are formed by the ionization of those interstellar neutrals. Following their convection into the outer heliosphere, the pickup ions are believed to be accelerated at the solar wind termination shock to become the anomalous cosmic ray component. Observations at 1 AU have confirmed that anomalous cosmic rays are, indeed, singly-charged, as predicted.

Heritage

The concept of an Interstellar Probe is not new. Previous to its inclusion in the Space Physics Strategy/Implementation Study of the Space Physics Division such a mission was recommended by both the Solar and Space Physics Panel and the Astronomy and Astrophysics Panel of the NAS/NRC study "Space Physics in the 21st Century - Imperatives for the decades 1995 to 2015. In addition, the scientific importance of this mission was recognized by previous NAS/NRC reports, including the 1992 report "The Decade of Discovery" (J. Bahcall, chairman), the 1982 report "Astronomy and Astrophysics for the 1980s" (G. Field, chairman), and the 1985 study "An Implementation Plan for Solar-System Space Physics" (S. M. Krimigis, chairman). With a mission of this scope international collaboration should be considered, and the 1992 International Space Year report included Interstellar Probe as a possible candidate for international collaboration.

Missions to Interstellar Space have been studied in the past, including the TAU[8] (Thousand AU) mission studied by JPL. Whereas TAU was directed mainly towards astronomical objectives, the present Small Interstellar Probe would have as its prime focus *in situ* measurements of particles, plasma, and fields at the boundary of the heliosphere and in nearby interstellar space.

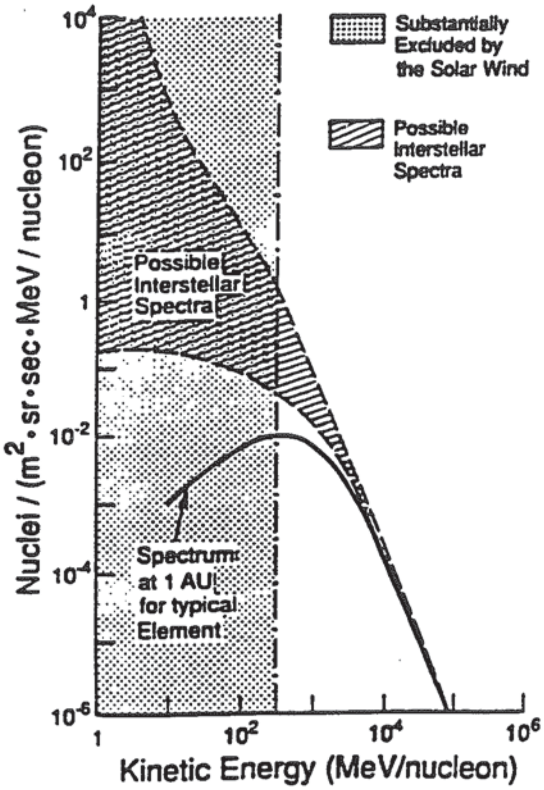


Figure 4: Cosmic ray spectrum for a typical element illustrating how low-energy cosmic rays are excluded from the heliosphere.

TRAJECTORY AND PROPULSION CONSIDERATIONS

Goals

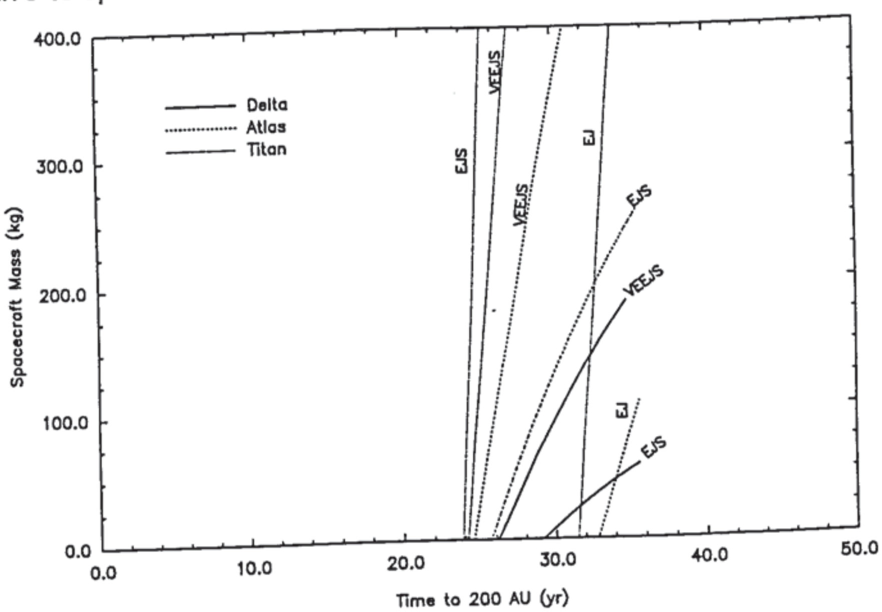
To accomplish its scientific objectives, an Interstellar Probe should acquire data out to a heliocentric distance of ~200 AU. To reach 200 AU within a reasonable mission lifetime (e.g., ~25 years or less), the spacecraft velocity must be several times greater than those of Pioneer-10 and the Voyagers, which range from 2.4 to 3.5 AU/year. In order to minimize the time and distance to the heliopause, the general direction of the trajectory should be toward the nose of the heliosphere, which corresponds to the ram direction of the inflowing interstellar gas. In the rest frame of the sun, the direction from which the interstellar flow is coming has ecliptic coordinates of +7.5° latitude and 254.5° longitude.

Trajectory Studies

The trajectory studies presented here consider only chemical propulsion because it provides adequate performance using current technology, although improvements in propulsion technology would clearly benefit this mission (see also below). Three launch vehicles were considered: Delta II, Atlas IIAS/Star 48B, and Titan IV/Centaur. All trajectories considered here use a Jupiter gravity assist to reduce post-launch ΔV; the epoch of the Jupiter flyby is adjusted to achieve the desired exit direction. This typically results in optimal trajectories every 12 years, with a window of about ± 1 year. We have also considered powered solar flybys, which provide improved performance, although the large maneuver near the Sun (several km/sec) will pose a significant technical challenge.

The simplest trajectories are the direct Jupiter flyby and the Jupiter gravity assist followed by a solar flyby. However, both of these trajectories require large launch energies and large post-launch ΔV, and they are not considered in this study. Moderate launch energy (C3 ~ 28 km^2/sec^2) may be achieved by performing a deep space maneuver followed by an Earth flyby. A Venus flyby followed by two Earth flybys achieves further reduction in launch energy (C3 ~ 16 km^2/sec^2). By varying the flight time to 100 and 200 AU, it is possible to calculate the net spacecraft mass that can be delivered (defined as the total spacecraft mass delivered minus propellant and propellant system). Both single-stage and two-stage propulsion are considered.

Figure 5 shows the net spacecraft mass vs. flight time to 100 and 200 AU for each trajectory and launch vehicle option, assuming single-stage propulsion. As expected, the Delta performs well only for the VEEJS trajectory. Note that the results for the larger launch vehicles are relatively insensitive to spacecraft mass.



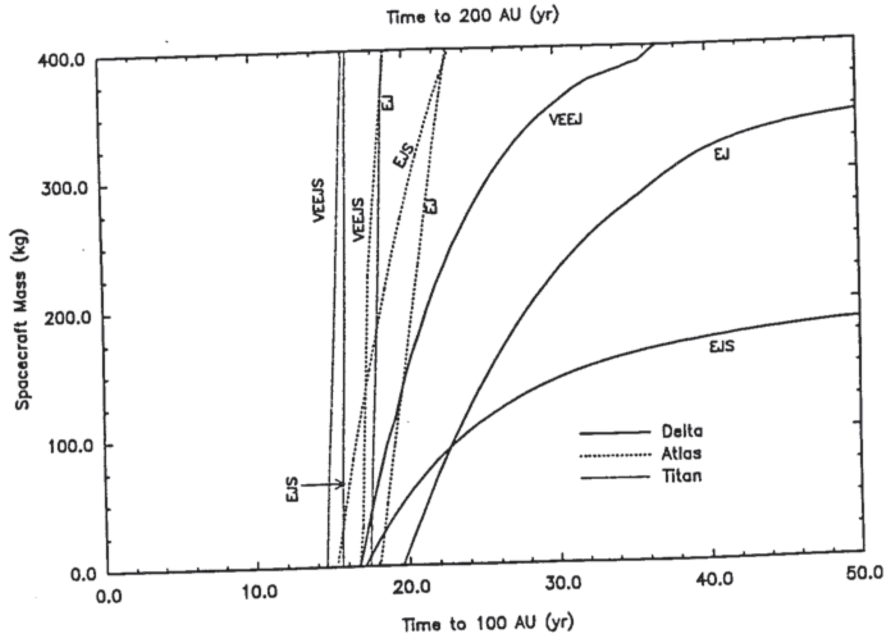
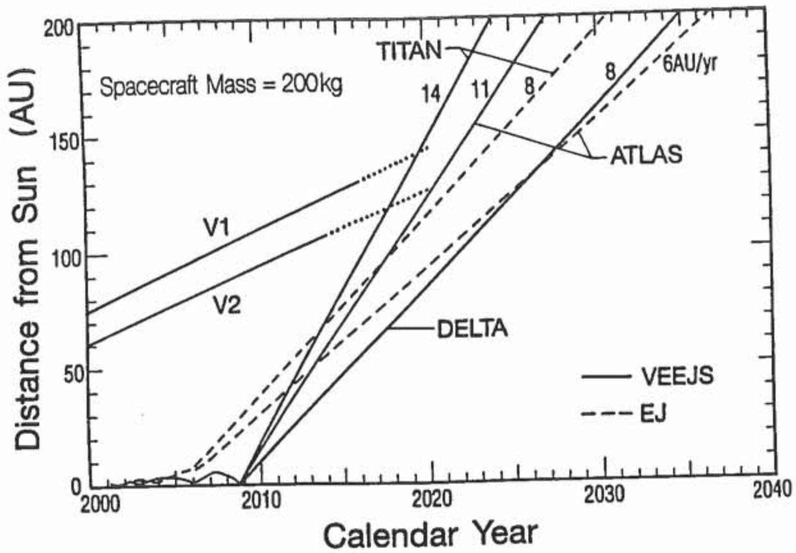


Figure 5: Elapsed times to reach 100 AU (bottom) and 200 AU (top) are shown as a function of spacecraft mass for three possible launch vehicles, and for trajectory options that include ΔV-Earth Jupiter gravity assist (EJ), ΔV-Earth Jupiter gravity assist with Solar Flyby (EJS), and Venus-Earth-Earth-Jupiter-Solar Flyby (VEEJS). Here single-stage propulsion with an Isp of 308 sec^{-1} was assumed. The studies were performed with the MIDAS software developed by Carl Sauer of JPL[9].

Figure 6: Heliospheric trajectories for a 200 kg Small Interstellar Probe using the EJ and VEEJS options are compared with those of Voyager 1&2, which may operate until ~2015. Average spacecraft velocities are labeled in AU/yr. These trajectories assume 2-stage propulsion with an Isp of 290 sec^{-1}.



Figures 6 and 7 show the two-stage results, which assume ideal staging, implying a somewhat optimistic mass estimate. To compensate, a conservative Isp of 290 sec^{-1} was assumed. Figure 6 shows the radial distance of a 200 kg spacecraft as a function of calendar year for the EJ and VEEJS options, assuming optimum launch times in the first decade of the 21st century. Voyager 1 & 2, expected to last until ~2015, are also shown. The two-stage results show considerable improvement over the single-stage options (compare Figures 5 and 7), with spacecraft velocities ranging up to ~14 AU/yr. It should be noted that the performance of a Proton rocket would be intermediate to that of an Atlas and a Titan in Figures 5, 6, and 7, while an Energia would further improve on the best performances shown.

Advanced Propulsion

The requirement to achieve escape velocities of ~10 AU/year suggests that advanced propulsion concepts should be considered. Nuclear electric propulsion would appear to be well suited, but the time scale on which it will become available is unclear. Solar electric propulsion would appear to have limited utility for a mission that must venture so far from the Sun. RTG-powered electric propulsion is an interesting possibility that warrants further study, since there will clearly be excess RTG power early in the mission. Finally, calculations indicate that a solar sail might also provide more than the required acceleration if unfurled at several tenths of an AU from the Sun. While it is unlikely that the costs associated with the development of any of these new propulsion technologies could be borne by this mission alone, Interstellar Probe might provide a very attractive opportunity to test a new propulsion system prior to its use in other applications, such as a manned mission to Mars.

SPACECRAFT

There are a number of key drivers for the design of the spacecraft for this mission; in many cases the mission can benefit from the development of new technology. The scientific instruments strongly favor a spinning spacecraft, presumably with the spin axis pointed at the Earth because of communication considerations. A spinning spacecraft would allow the particle and plasma instruments to cover a broader field of view, and it would benefit the magnetometer in correcting for the residual spacecraft field.

A mission lifetime of up to 25 years involves rather complex redundancy issues and requires an efficient radio-isotope power source. The possibility of multiple spacecraft should also be considered. If the trajectory involves close flybys of Jupiter and/or the Sun, rad-hard electronics and/or shielding may be required. Thermal protection during a solar fly-by would

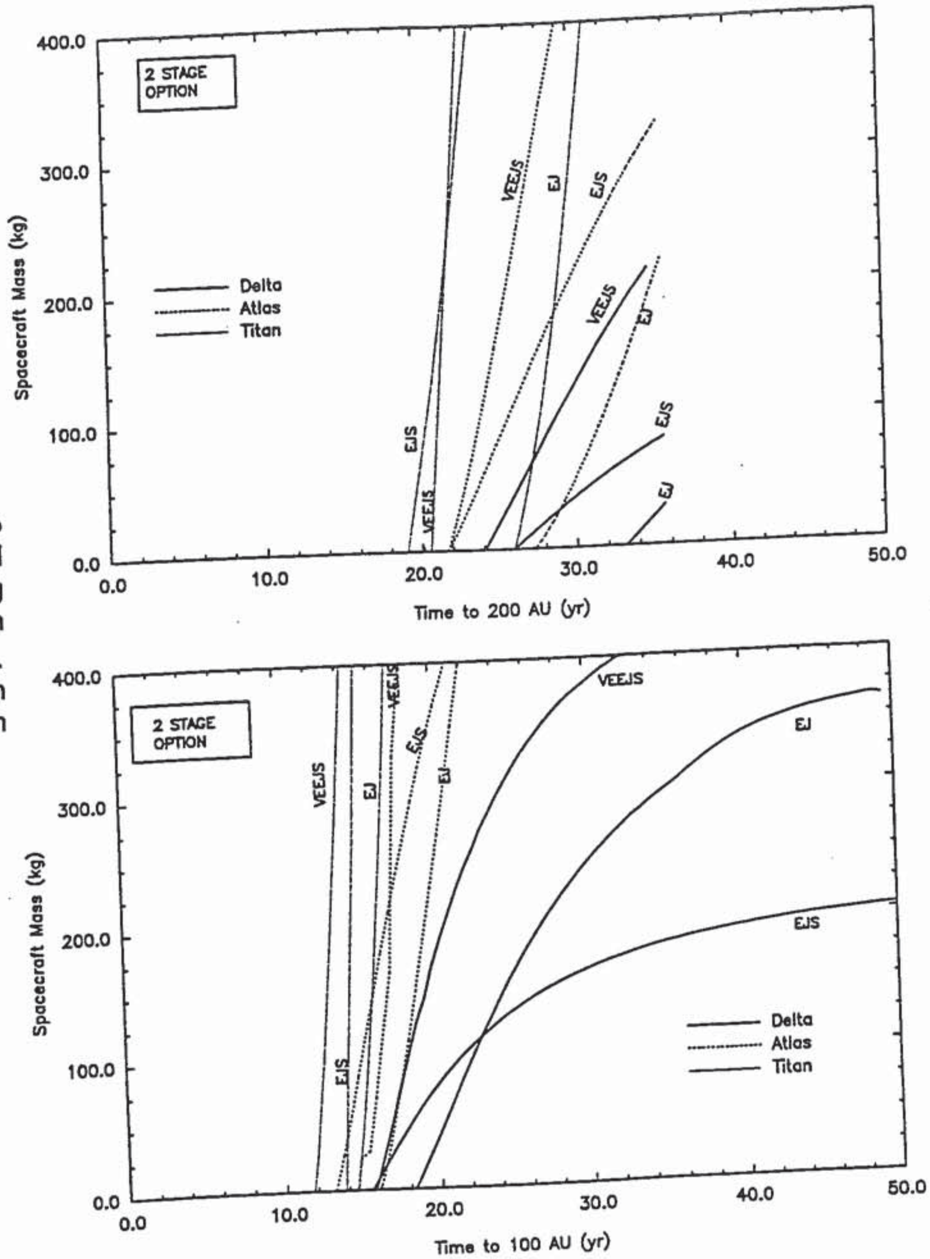


Figure 7: Elapsed time to reach 100 AU (bottom) and 200 AU (top), assuming ideal 2-stage propulsion with an Isp of 290 sec^{-1}. Trajectory and launch vehicle options are listed in the caption to Figure 5.

make use of technology developed for the Solar Probe mission. The large post-launch ΔV maneuvers could benefit from advanced solid/liquid propulsion with multiple stages. Data would presumably be recorded onboard and dumped periodically to the DSN. Communications from ~200 AU would clearly benefit from advanced technology.

While there has to date been no funding available to study spacecraft designs for a Small Interstellar Probe, it is clear that many of the issues are common to the Solar Probe and Pluto-Flyby missions, and that Interstellar Probe could benefit greatly from new technology developed for those missions. Stated differently, a common spacecraft design might serve all three exploratory missions.

INSTRUMENT REQUIREMENTS

In the 1990 study a strawman payload requiring 125 kg and 96 W was identified, including several high-resolution energetic particle spectrometers, and comprehensive plasma studies. Fortunately, advances in space borne instrumentation now make it possible to fly state-of-the-art sensors with greatly reduced resource requirements, as demonstrated in a recent NASA workshop on small instruments[5]. It should also be recognized that the collecting power requirements for instruments on this mission are in many cases reduced from those near 1 AU by the extended time and distance scales involved. Considerable savings in instrument resources can also be achieved by employing common power supplies and a common data processing unit. Data rate requirements can be greatly reduced by on-board processing and data compression techniques, now feasible with modern processors. As a result, the principal scientific goals of this mission can be accomplished with a much smaller payload.

Table 1 compares the strawman payload identified in the 1990 report with a reduced payload that preserves the essential measurement capabilities (with the exception of the IR spectrometer, which is no longer included). Resource requirements for the Small Interstellar Probe payload are based on inputs from a variety of scientists, but have not as yet been studied in any detail. It is therefore possible that the payload goal of 20 kg and 20 W, assumed to be compatible with a ~200 kg spacecraft, can be achieved with further study, without sacrificing any key scientific goals of the mission.

Table 1 - Small Interstellar Probe Science Payload

	1994			1990 Study		
Instrument	Mass (kg)	Power (W)	Data rate@ 200AU (bps)	Mass (kg)	Power (W)	Data rate@ 200AU (bps)
Magnetometer	1	0.5	1	4	4	1
Plasma waves, radio	3	3	5	11	6	30
Neutral H, He, O	3	3	4	4	5	10
Energetic neutral atoms						
Interstellar plasma ions (+ & -)	4	4	10	20	14	20
Interstellar & solar wind electrons						
Solar wind ions						
Interstellar plasma mass & charge comp.	6	6	5	25	20	75
Suprathermal & pickup ions						
Anomalous/galactic cosmic ray isotopes	3	2	3	22	17	40
Cosmic ray H, He, & electrons	2.5	2	5	10	10	30
Gamma ray bursts	0.5	1	3			
UV photometer	0.5	0.5	1	1	1	10
Dust	1.5	1.5	0.1	8	9	10
IR Spectrometer	not included			20	10	10
Subtotal	25	23.5	37	125	96	236
DPU	2	1.5	0			
Total	27	25	37			
Goal	20	20	50			

RELATION TO PIONEER AND VOYAGER

The Voyager and Pioneer missions have provided our first exploratory look at the three dimensional structure of the heliosphere. It is likely that over the course of their lifetimes one or more of those spacecraft will cross the termination shock, and it is even possible that one may reach the heliopause, thereby defining the scale size of the heliosphere, and providing valuable exploratory data. The Small Interstellar Probe considered here would greatly extend those pioneering ventures by providing detailed, comprehensive measurements with modern, more capable instrumentation specifically designed to observe the boundaries of the heliosphere and the interstellar medium itself. Table 2 compares the capabilities of the strawman payload with those of the Voyagers. If a Small Interstellar Probe were launched near the turn of the century, there might also be opportunities for valuable multi-spacecraft studies of the boundaries of the heliosphere.

Table 2 - Comparison of Voyager and Small Interstellar Probe Capabilities

	Voyagers	Small Interstellar Probe	Comments
Maximum distance	130 AU (V1) 107 AU (V2)	≥200 AU	
Spacecraft speed	3.5 AU/yr	≥10 AU/yr	Various options possible
Spacecraft Orientation	3-axis stabilized	Spinning	Provides 3-D coverage for many studies
Data rate	46.6 bps at 100 AU when tracked	50 bps at 200 AU continuous	Higher data rates possible closer to Earth
Measurement Capabilities			
Magnetic fields	Yes	Yes	Adequate for expected fields
Plasma waves			
Electric fields	Yes	Yes	Both E & M required to identify wave modes
Magnetic fields	No	Yes	
Distant solar wind			
Protons	to 107 AU	Yes	3-D dynamics/composition of distant solar wind and sub-sonic post-shock plasma
Alphas	to 60 AU	Yes	
Electrons	to 5 AU	Yes	
Interstellar pickup ions	No	Yes	Composition and dynamics
Interstellar plasma			
Density, veloc., temp.	No	Yes	3-D dynamics/composition for $1 \leq Z \leq 28$ and $1 \leq A \leq 60$
Elem./isotopic composition	No	Yes	
Charge states	No	Yes	
Suprathermal particles			
Protons, alphas, electrons	No	Yes	From ~20 keV/nuc to a few MeV/nuc
Elemental composition	No	Yes	
Charge states	No	Yes	
Anom./galactic cosmic rays:		Yes	
Element energy spectra	Yes	Yes	Z = 1 to 28 over energies from ~5 to several hundred MeV/nuc
Isotopic composition	$Z \leq 14$	Yes	
Electrons	Yes	Yes	Positrons also important
Interstellar neutrals	No	Yes	Measure extinction with radius
Dust	No	Yes	Sensitivity to $\geq 10^{-15}$ g
UV flux	to 76 AU	Yes	Density profile of interstellar H
Gamma-ray bursts	No	Yes	Long baseline triangulation

SUMMARY

We conclude that with current technology a Small Interstellar Probe can be targeted to explore the boundaries of the heliosphere and nearby interstellar space, thereby defining the scale of the heliosphere, and establishing its role in the Galaxy. There are a variety of launch vehicle and trajectory options available that can propel a small, innovative spacecraft weighing ~200 kg to distances of ~200 AU at velocities ranging from ~6 to ~14 AU/yr. By taking advantage of recent technological advances, this probe could carry an advanced scientific payload capable of a broad range of exploratory studies that far exceed those that are possible with the Pioneer and Voyager missions. In view of the fundamental contributions that this mission would make to studies that include space plasma physics, nucleosynthesis, stellar and galactic evolution, astrophysics, and cosmology, it is important that NASA and other space agencies give serious consideration to this truly exploratory mission.

ACKNOWLEDGMENTS - We appreciate contributions from a variety of individuals, including A. Cummings, C. Elachi, M. Evans, M. Forman, M. Gruntman, W. Kurth, T. Holzer, K. Hurley, V. Jones, D. Judge, F. McDonald, E. Mobius, F. Mozer, D. Schemansky, E. Smith, E. Stone, B. Tsurutani, and M. Witte. The work was at JPL was funded under contract to NASA; the work at Caltech was supported by NASA grant NAGW-1919.

REFERENCES

[1]Holzer, T. E., Ann. Rev. Astron. Astrophys., 27, 199, 1989.

[2]Suess, S. T., Rev. Geophys. 28, 1, 1990.

[3]Holzer, T. E., R. A. Mewaldt, and M. Neugebauer, The Interstellar Probe: Scientific Objectives and Requirements for a Frontier Mission to the Heliospheric Boundary and Interstellar Space. Report of a Workshop held March 20-21, 1990 in Ballston Va.

[4]Space Physics Strategy-Implementation Study, The NASA Space Physics Program for 1995 to 2010, April, 1991.

[5]"Small Instruments for Space Physics", Proceedings of a workshop held March 29-31, 1993 in Pasadena, CA, B. T. Tsurutani, ed.

[6]Gurnett, D. A., W. S. Kurth, S. C. Allendorf, and R. L. Poynter, Science, 262, 199, 1993.

[7]Cummings, A. C., E. C. Stone, and W. R. Webber, J. Geophys. Research, in press, 1994.

[8]"Preliminary Scientific Rationale for a Voyage to a Thousand Astonomical Units", JPL Publication 87-17, M. Etchegaray, ed., 1987.

[9]Sauer, Carl G. Jr., Journal of Astronautical Sciences, 3, 251, 1989.